

# Tuning order in cuprate superconductors

Subir Sachdev<sup>1\*</sup> and Shou-Cheng Zhang<sup>2†</sup>

<sup>1</sup>Department of Physics, Yale University, P.O. Box 208120, New Haven, CT 06520-8120, USA

<sup>2</sup>Department of Physics, Stanford University, Stanford, CA 94305, USA

\*URL: <http://pantheon.yale.edu/~subir>

†E-mail: [sczhang@stanford.edu](mailto:sczhang@stanford.edu).

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**This article presents our perspective on STM measurements by Hoffman *et al.* *Science* 295, 466 (2002) of the vortex lattice in  $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$ . We discuss implications of these measurements for various theories of the cuprate superconductors.**

In 1986, superconductivity—the ability to transport electrical current without significant resistance—was discovered in cuprate compounds. These materials have fascinated physicists ever since, in part because of the high critical temperatures ( $T_c$ 's) below which superconductivity is present and the consequent promise of technological applications. However, cuprate superconductivity also raises fundamental questions about the collective quantum properties of electrons that are confined to a lattice and interact with each other (the “correlated electrons” problem). Hoffman *et al.* (1) have recently reported an innovative scanning tunnelling microscopy (STM) study which should help answer some of these questions.

All discussion of the cuprates begins with the compound  $\text{La}_2\text{CuO}_4$ . Its valence electrons reside on certain  $3d$  orbitals on the Cu ions which are arranged in layers. In each layer, the Cu

ions are located on the vertices of a square lattice, and the ability of electrons to hop between successive layers is strongly suppressed by the negligible inter-layer overlap of the 3d orbitals.  $\text{La}_2\text{CuO}_4$  is an insulator; its inability to transmit electrical current within a layer is a result of the Coulomb repulsion between the electrons which localizes them on the Cu sites. Moreover, it is known that the spins of the electrons are oriented ‘up’ and ‘down’ in a checkerboard pattern as shown in Fig. 1a: this quantum phase (or state) is called an insulator with ‘Néel’ or antiferromagnetic order.

If we keep the material at zero temperature and tune another parameter, such as the charge carrier concentration or the magnetic field, we can explore different quantum states of the system. For example, the properties of  $\text{La}_2\text{CuO}_4$  change when mobile charge carriers are introduced into the insulating Néel state by chemical doping. In  $\text{La}_{2-\delta}\text{Sr}_\delta\text{CuO}_4$ , a fraction  $\delta$  of the electrons is removed from the square lattice. The motion of the resulting holes is no longer impeded by the Coulomb interactions and for  $\delta > 0.05$  the quantum state (at zero K) of the electrons is a superconductor; this superconductivity is present at all temperatures below  $T_c$ .

For  $\delta > 0.2$  and at low temperatures, the cuprates appear to be qualitatively well described by the well-established Bardeen-Cooper-Schrieffer (BCS) theory of superconductivity. In this theory, the mobile electrons form pairs that condense into a quantum state extending across the system. A gentle spatial deformation of this state can set up a “superflow” of pairs, leading to the phenomenon of superconductivity. However, the internal wavefunction of the electron pairs has an unconventional structure in the cuprates: the spins of the electrons are oriented so that the total spin of the pair is zero, but their orbital motion around each other is described by a wavefunction with *d*-wave symmetry. In most low  $T_c$  superconductors studied prior to 1986, this wavefunction has an *s*-wave symmetry.

During the last decade, the debate has centered on the nature of the quantum state of the cuprates at intermediate  $\delta$ — between the well understood limits of the Néel insulator at  $\delta = 0$

and the BCS superconductor at larger  $\delta$ . Many candidate states have been proposed. A useful way of characterizing them is in terms of different types of “order”, usually associated with breaking the symmetry of the electronic ground state. For example, the Néel state breaks the symmetry of spin rotations and lattice translations, and the superconductor breaks the symmetry of charge conservation.

First, the order may be a spatial modulation of the local spin or charge density (2, 3, 4, 5). The simplest example is the Néel state found in the insulator at  $\delta = 0$ , and shown in Fig. 1a. This state can be viewed as a wave in the spin density, with a wavelength of two lattice spacings in the  $x$  and  $y$  directions. At non-zero  $\delta$ , the wavelength of the spin density wave changes; the orientation and period of this more complex wave is described by a  $\delta$ -dependent wavevector  $\mathbf{K}$  (Fig. 1b). A charge density wave accompanies most such spin density waves, with a wavevector of  $2\mathbf{K}$  (6). These spin and/or charge density waves are present at small  $\delta$ , and eventually vanish at one or more quantum critical points leading to full restoration of invariance under spin rotations and lattice translations.

In this picture, the order associated with superconductivity, and with spin and charge densities should provide the foundation of a theory of the cuprates at all  $\delta$ . At low  $\delta$ , the spin density wave order dominates, resulting in a Néel state; at high  $\delta$ , the order associated with superconductivity dominates; at intermediate  $\delta$ , the two compete.

Second, the order may be associated with the fractionalization of the electron (7, 8). In certain theoretically proposed quantum states, it is known that the electron falls apart into independent elementary excitations, which carry its spin and charge (such states need not break any symmetry). Experimental tests for fractionalization have, however, not yielded a positive signature so far (9, 10). A third set of proposals (11, 12, 13) focuses on a rather unconventional order linked with a spontaneous appearance of circulating electrical currents, and an associated breaking of time-reversal symmetry.

Given the distinct signatures of these proposals, one might expect that experiments can resolve the situation quite easily. However, the difficulty of smoothly varying the value of  $\delta$  while maintaining sample quality and avoiding extraneous chemical effects has hampered progress. A recent set of experiments (14, 15, 16, 17, 18), and especially in those reported by Hoffman *et al.* (1), has led to a breakthrough. These experiments show that it is possible to “turn a knob” other than  $\delta$  to tune the properties of the cuprate superconductors. The “knob” is a magnetic field applied perpendicular to the layers. Detailed dynamic and spatial information on the evolution of the electron correlations as a function of the applied field has been obtained. These data should help solve the mystery of the cuprates.

Hoffman *et al.* studied a cuprate superconductor in an applied magnetic field by a novel STM technology of atomically registered spectroscopic mapping. The field induces vortices in the superconducting order. Around each of the vortices is a superflow of electron pairs. An innovative analysis of the large amounts of STM data, with very high spatial and energy resolution, enables Hoffman *et al.* to factor out the substantial noise generated by chemical impurities introduced through doping, and test directly for orders other than superconductivity.

Theoretical studies pointed out (5, 19) that the suppression of superconductivity in the vortex cores should induce local magnetic order. This repulsion between the superconducting and magnetic orders also appears in theories of magnetic quantum phase transitions in the superconductor (4, 5, 20). Combining these past works with insights gained from the neutron scattering experiments by the group of Aeppli (15, 21), Demler *et al.* (22) have pointed out that dynamic spin density wave correlations (like those in Fig 1b) should be enhanced in the regions of superflow which surround the much smaller vortex cores. Static order in the associated charge density wave has been proposed (23), in coexistence with dynamic spin fluctuations and well-established superconductivity. (see Fig 2).

Consistent with these expectations, the STM observations show a clear modulation with a

period of four lattice spacings in the electron density of states around the vortices, in regions which also display the characteristic signatures of electron pairing associated with superconductivity. Moreover, the wavevector of this ordering is  $2\mathbf{K}$ , where  $\mathbf{K}$  is the wavevector for spin density wave ordering observed in neutron scattering (15) (albeit in a different cuprate superconductor). The observed field dependencies of the neutron scattering intensities (15, 17, 18) are also consistent with theoretical expectations (19, 22).

These observations are compelling evidence that the order competing with superconductivity is the first of those discussed above: a slight suppression of superconductivity reveals a modulation in observables linked to the electron charge density. This coexistence region between superconductivity and the competing order should yield interesting new insights into the fundamental properties of cuprates. Similar modulations should be observable around other regions of the sample where the density waves can be pinned, for example near impurities within the Cu plane.

The scope for further studies using the magnetic field as a tuning parameter is also wide. It should be possible to tune the cuprates to the vicinity of quantum phase transition(s) associated with the spin and charge ordering. Similar field-tuned studies can also be carried out in other correlated electron systems, including the electron-doped cuprates, organic superconductors, and intermetallic compounds known as the heavy-fermion materials.

The next challenge will be to use our understanding of the low temperature properties of the cuprate superconductors to formulate a theory of competing orders above  $T_c$ . Here many mysteries remain, particularly the microscopic origin of the “pseudogap” behavior, that is, the appearance of features characteristic of energy gap of the superconducting state at temperatures well above  $T_c$ .

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**Fig. 1. Electron spin configurations on the square lattice of Cu ions.** The arrows represent the direction and magnitude of the average spin moment. The blue shading represents the average electron charge density on each Cu site. (a) Néel state in the insulator at  $\delta = 0$ . The spins oscillate with a period of 2 lattice spacings in the  $x$  and  $y$  directions. (b) Density wave at a moderate value of  $\delta$ . A single period of 8 lattice spacings is shown along the  $x$  direction, while the period along the  $y$  direction remains at 2 lattice spacings. Unlike Fig. 1a, the magnitude of the spin moment, and not just its orientation, changes from site to site; we can also expect (6) a corresponding modulation of the charge density on each site. The wavelength of the charge density wave is half that of the spin density wave in both directions.

**Fig. 2. Magnetic field penetration of a superconductor in a vortex state and the associated order.** The superconducting order is suppressed at the cores of the vortices (red dots). Superconducting currents (white loops) circulate around the vortex cores. Experiment and theory discussed in the text indicate that spin and charge orders depicted in Fig. 1b can exist in the vortex state. The colored surface shows the envelope of this order parameter, superimposed on the vortex lattice. This type of order can be static or dynamically fluctuating depending on the doping level and the magnetic field. The spacing between the vortex cores is proportional to the inverse square root of the applied magnetic field, and is typically about fifty times the spacing of the lattice in Fig. 1.



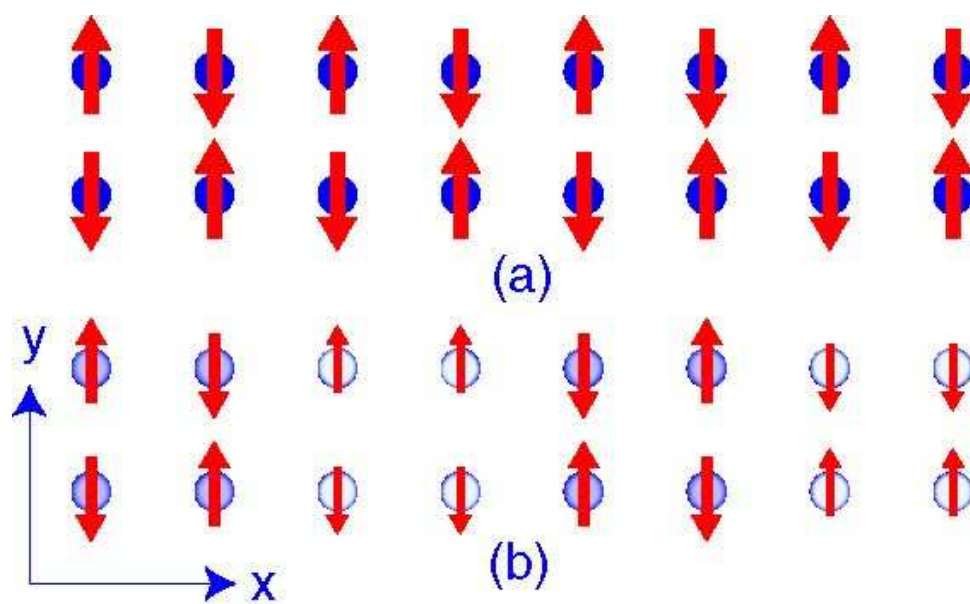


Figure 1:

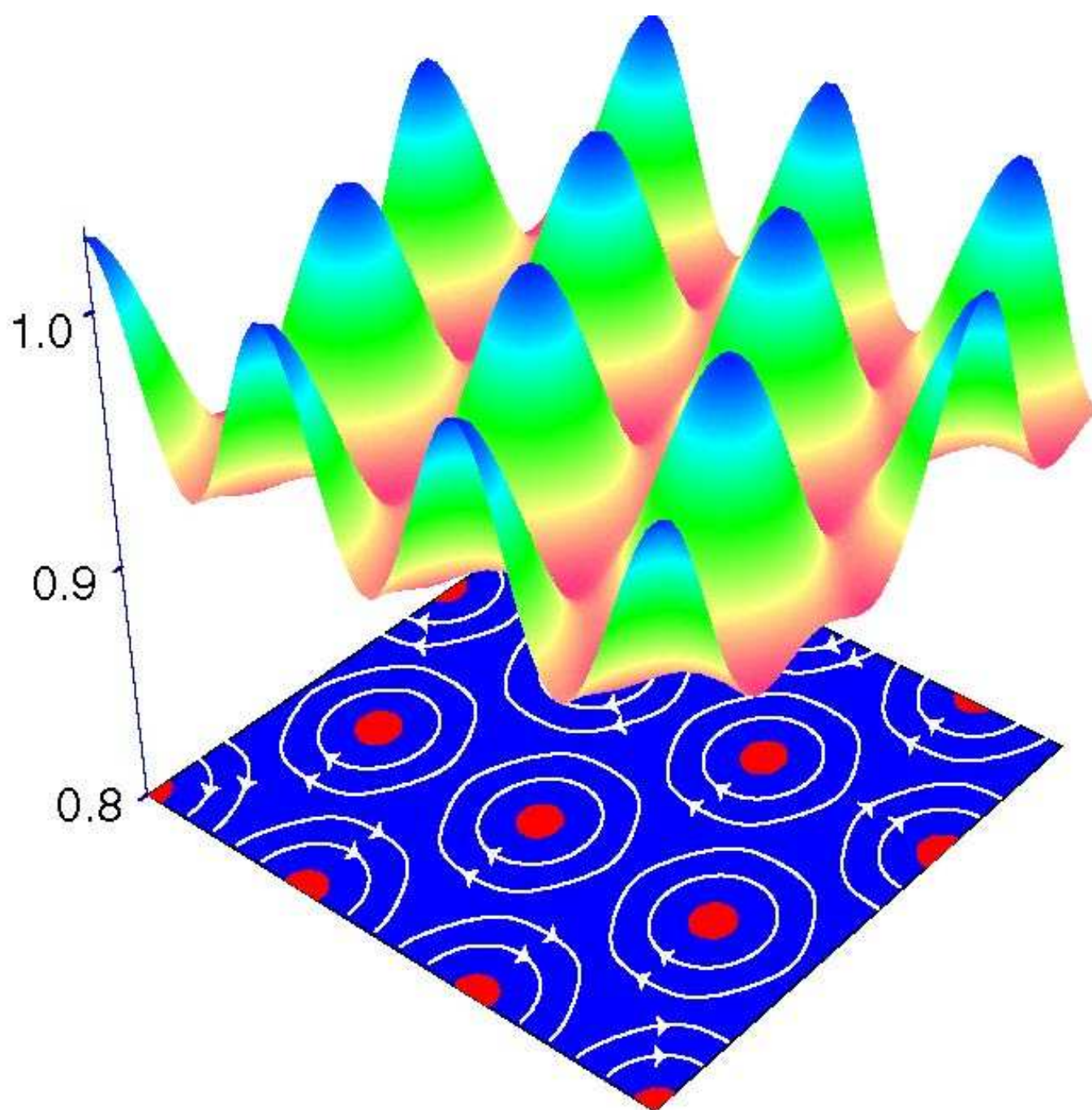


Figure 2: